BeatMag 💙 – An In-Deth Magnetocardiographic Analysis

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Abstract

BeatMag 💔 introduces a transformative paradigm for magnetocardiography (MCG) by shifting from averaged heartbeat analysis to a fully resolved beat-to-beat methodology. Classical MCG analysis can suppress physiologically meaningful non-periodic events. BeatMag 💔 – utilizes the unparalleled sensitivity and specificity of shielded quantum sensing technology and advanced signal processing for high-resolution cardiac diagnostics. This framework demasks arrhythmic, ischemic, autonomic, and repolarization-based phenomena which are frequently not visible due to averaging within established MCG methods, as a dynamic biomagnetic modality with significant clinical and scientific relevance.

Background: Conventional magnetocardiography (MCG) is based on averaging multiple heartbeats (sometimes hundreds in the case of room temperature sensors), which suppresses noise but can also result in the loss of clinically relevant information.

Objective: Establish beat-to-beat MCG using Superconducting Quantum Interferometer sensors (SQUIDs) in a magnetically shielded room (MSR), achieving high-resolution characterization or analysis of individual heartbeats.

Methods: Using an extended analysis pipeline, R-peaks are detected, beats segmented, normalized, filtered, and parameterized. Beat sequences are arranged chronologically and supplemented with metadata.

Results: SQUID measurements performed within an MSR achieve a sensitivity of <10 fT, enabling high-resolution detection of individual beat morphologies and repolarization microfeatures, as no averaging is required.

Conclusion: BeatMag 💔 enables the investigation of sympathetic-associated repolarization dynamics, transient ischemia, arrhythmic micro-patterns, and PRD-like oscillations, laying groundwork for next-generation diagnostic methods.

1. Introduction

A magnetocardiography system (MCG) consists of a medical device that measures the magnetic field generated by the contraction of myocardial cells. The intracellular and membrane ion flows work like bar magnets that behave proportionally to electrical heart activity, as we know from ECGs, for example.

Similar to an ECG, MCG is a passive measurement, meaning that data acquisition is non-invasive and does not require any contrast agents or electromagnetic radiation. The advantage is that the magnetic fields penetrate human tissue without loss and can be measured directly on the chest using quantum sensors. The intracellular currents e.g. are isolated from the membrane and cannot be captured by an ECG.

MCG procedure transforms periodic cardiac magnetic field signals into averaged templates for analysis. Even though this approach can open the path to high precision diagnosis, critical transient phenomena such as micro-ischemia, arrhythmogenic precursors, repolarization instability, and sympathetic modulation suffer from this superposition technique. However, with a poor signal-to-noise ratio, this approach could be crucial.

Optically pumped magnetometers (OPMs), for example, suffer from drift, thermal instability, sensor-dependent calibration, and noise in the range of 20‑50 fT. Even though they or unshielded acquisition methods may be suitable for averaged MCG, even modern methods, e.g., from the field of artificial intelligence (AI), will not be able to achieve beat-level precision to resolve the required microamplitude patterns.

Superconducting quantum interference devices (SQUIDs) in a magnetically shielded room (MSR) provide industry-leading sensitivity (<10 fT) and enable the detection of cardiac characteristics in the sub-pico-tesla or femto-tesla range. Long-term stability and channel reproducibility make SQUIDs the only practical platform for heartbeat-to-heartbeat analysis. SQUID sensors are highly sensitive quantum sensors used to measure very small changes in magnetic fields. Cooled with liquid helium (LHe), they operate on the principles of superconductivity and the Josephson effect, enabling them to detect magnetic fluxes well below the quantum limit, see Malmivuo et al. [19].

Thus, while work is still ongoing on room temperature sensor technology, such as OPMs, to generate a sufficiently accurate averaged signal for a conventional MCG, we have already shifted our focus to providing a high-precision beat-to-beat MCG using shielded SQUID-based systems.

BeatMag 💓 aims to fully preserve the temporal diversity of the heart's biomagnetic signals. Each heartbeat is isolated, parameterized, and interpreted in a physiological and biophysical context, such that the entropy contained in each MCG signal is unleashed in its entirety.

3. Materials and Methods

The objective is to analyze the individual heartbeat cycle in chronological order of the overall MCG signals. Instead of using an averaged heartbeat in a specific phase as a reference signal, each heartbeat is now continuously analyzed, individually parameterized, and then evaluated in its entirety, see Dischl et al. [7] or Shin et al. [28].

For this purpose, data will be analyzed that was generated using technology from Biomagnetik Park GmbH (bmp), i.e., using the medical devices CS Mag II and III. This means

that the MCG data acquired with shielded SQUIDs, i.e., with up to 64 sensors, is processed and stress measurements during and after ergometry are available. Furthermore, there are signals that were measured in the z-direction (CS Mag II), as well as those that were measured in all spatial dimensions.

BeatMag 💔 will be implemented on a modern C# framework, which is based on software from bmp Cardio Expert 2.5. That means that the initial preprocessing remains essentially the same, i.e., R-peak detection and registration, calculation of a reference signal, and segmentation. However, all identified heartbeats are saved separately. The segmentation of the reference signal is used as a reference pattern for the subsequent analysis. Each detected heartbeat is processed analogously to the reference signal and analyzed separately. Due to the computational effort and analyzability, the evaluation can be limited to a defined phase within the MCG data. However, the outcome will be a sequence of parameters in chronological order.

4. Results

BeatMag 💔 not only includes the impact of previous "standard" MCG analyses. It also provides the dynamic variations from beat to beat for each individual bmp parameter. Thus, the scientific impact comprises a new research area that combines beat-to-beat MCG and biophysical modeling. It could close a gap that has resulted from modern signal processing methods such as deep learning (DL), e.g. Tao et al. [30]. These methods often have issues with measurements performed using different systems or protocols. Furthermore, these dynamic parameter sequences can be processed using AI methods such as machine learning (ML), e.g. Mockler et a. [20] or Tao et al. [29]. Simultaneous and/or autonomous analyses are not excluded and open access to the maximum entropy of an MCG measurement.

9. Discussion

The results highlight both the potential and the current limitations of beat-to-beat MCG. Since MSR-shielded SQUID-based MCG systems enable unparalleled temporal resolution and magnetic sensitivity, the reliance on specialized infrastructure currently restricts their availability in widespread clinical environments. However, the method addresses key limitations of existing MCG approaches, particularly the loss of transient and non-periodic phenomena through averaging. By providing fully resolved beat sequences enriched with physiological metadata and biophysical interpretability, BeatMag 💔 offers a pathway toward more precise diagnostics and personalized cardiac diagnosis.

Furthermore, the method complements modern AI systems by offering curated, high-quality time-series data that reduce the variability challenges typically encountered when models are trained on heterogeneous measurements from different sensor types or acquisition protocols. Future work should explore the integration of beat-to-beat MCG with multimodal datasets, assess its prognostic potential in larger cohorts, and evaluate its utility in detecting early cardiac dysfunctions, including micro-ischemia, HFpEF signatures, and autonomic imbalance. Continued refinement of sensor technology—potentially including next-generation room-temperature quantum sensors—may broaden the applicability of this

method. Nevertheless, the current findings demonstrate that beat-to-beat MCG represents a highly promising platform for next-generation cardiac diagnostics and computational electrophysiology.

10. Conclusion

BeatMag 💔 establishes a new methodological and technological standard for magnetocardiography by providing a beat-to-beat analysis based on shielded SQUID sensor technology. By eliminating the limitation to averarged signal analysis, the approach acesses the full temporal and physiological richness of cardiac magnetic activity. It allows the detection of subtle electrophysiological events such as transient ischemia, arrhythmogenic micro-patterns, autonomic modulations, and sympathetic-associated repolarization dynamics. The high stability and ultra-low noise environment of LHe-cooled SQUID systems in an MSR make it possible to capture repolarization microfeatures that remain inaccessible to room-temperature sensing technologies. BeatMag 💔 therefore represents a paradigm shift toward high-resolution, entropy-preserving biomagnetic diagnostics and lays the groundwork for future clinical applications, risk stratification tools, and AI-driven analytics.

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